Propellantless propulsion in magnetic fields by partially shielded current

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I. Introduction

Electrodynamic tethers have been studied intensively for propulsion and power generation purposes in a number of different scenarios.[1] An electrodynamic tether exploits the magnetic field of a planet via the Lorentz force acting on it when the tether is transversed by a current. In order for the concept to work the current flow in the tether needs to be closed using the plasma surrounding the satellite. This introduces stringent bounds on the available currents, which must be compensated by making the tethers very long thus increasing the bare tether surface. As an example we reference to the several kilometers long tether recently proposed by Sanmartin and Lorenzini for the exploration of the Jupiter moons.[2] The mission has been later studied in greater detail by Sanmartin in cooperation with the Advanced Concepts Team of ESA[3] and revealed a number of design issues that need to be addressed and that derive ultimately from these limitations. The need to rely on the plasma and the need for very long tethers could be eliminated altogether if it was possible to close the circuit with a wire rather than via the plasma. However, this seems to be ruled out, as the net electromagnetic force acting on a closed wire immersed in a uniform magnetic field cannot yield a propulsive force (a net angular momentum is still possible, though). In a non-uniform magnetic field a net force in the direction of increasing magnetic field strength is still encountered, which may be used effectively under laboratory conditions[4] but appears to be hopeless for any applications in space.

To circumvent this caveat, part of the current must be shielded from the magnetic field in which the satellite moves, which is indeed possible by means of a superconductor.[5,6] The use of superconductors in space mission concepts is not too unusual. Superconductive coils have been proposed for propulsion concepts,[7,8] advanced shielding devices[9] and fly-wheel systems. The use of superconductors as a shield from the surrounding magnetic field has

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been suggested for different reasons elsewhere.[10,11] Some recent advances in superconductive wires manufacture[12–15] has revived the hope that these concepts may actually be near to an implementation in a space system. Though the current knowledge base from space experiments with superconductors is yet rather limited, the actual results[16–19] are very promising if one considers the robustness to the space-environment of high-temperature superconductors and the associated chill components.

In this paper we describe the basic functioning of an original device based on the use of superconductors partially shielding a current on board of a satellite and therefore allowing for a significant net Lorentz force on a closed circuit. Depending on the exact conditions (characteristics of the orbit) we describe several working modes of the device. Below geostationary orbit it seems to be very promising in transforming, without the use of propellant, spacecraft power into propulsion or spacecraft kinetic energy into power. Above geostationary orbit it allows a propellantless and powerless propulsion mechanism.

II. Description of the Device

We consider a satellite in the orbit of a planet with a magnetic field, for example the Earth, Jupiter or Saturn. Putting a closed wire on board of the satellite in which a current I flows, this current will interact with the magnetic field of the planet but it will fail to generate a significant net force on the spacecraft. By shielding a part of the wire from the magnetic field, a situation similar to an electrodynamic tether emerges and a net force is found that can be used for propulsion or may simply generate power. This can be achieved by placing those parts of the wire to be shielded into a superconductor having cylindrical geometry with sufficiently thick walls (see Willis[20] for a study on the shielding capabilities of HTS hollow cylinders). It is a well-known characteristic of superconductors that a magnetic field cannot penetrate them. Now a net force results on the unshielded part of the wire and in this way on the satellite (cf. the schematic depiction in figure 1). As the satellite has to be equipped with a superconductor, it is self-evident to build the wire with a superconducting material as well. In this way the advantage over electrodynamic tethers, i.e. the larger currents available, is maximized. Currents in superconductors can reach levels as high as 10^6 A/cm^2,[12–15] which shrinks the total length of the wire to the order of 1m as will be shown below. Note that the total energy change of the satellite, due to the applied force, is balanced by an opposite change in the energy of the source of the magnetic field: the plasma underneath the Earth crust. In this sense our device, and so the electrodynamic tethers, are able to extract energy from the rotation of a planet using its magnetic field as a medium.

In the following we give a rough estimate of the efficiency of the device as a propulsion system. We consider that the Earth magnetic field is a dipole aligned with the Earth axis

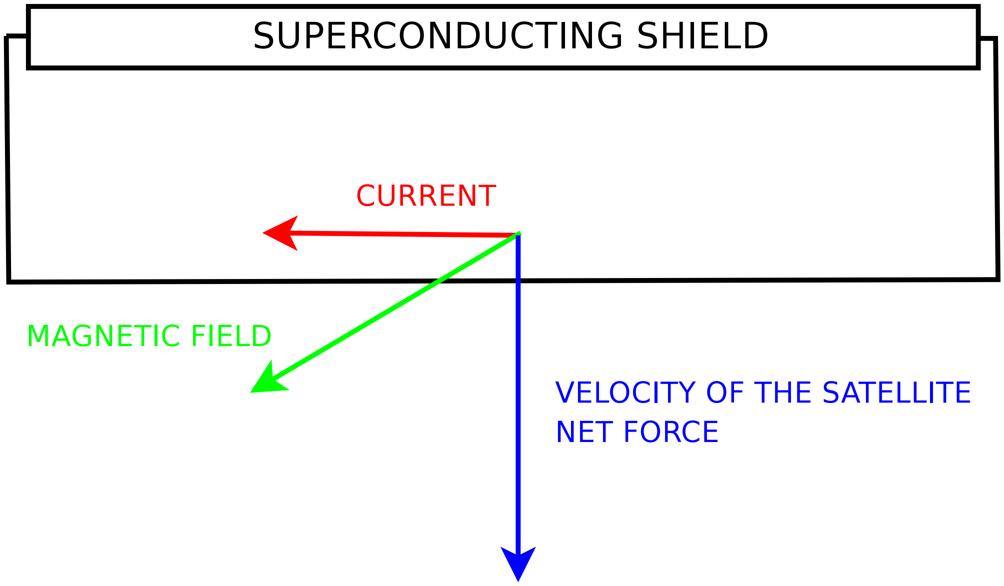

Figure 1. Schematic three-dimensional depiction of the device. As explained in the text it may be useful to align the current perpendicular to the velocity and to the magnetic field. The net force need not be aligned exactly with the velocity in realistic applications.

of rotation and we consider only satellite orbits with zero inclination.

A. Lorentz force and its implications

The total movable charge (electrons) in the wire with length l exposed to the magnetic field is called Q. For a given charge density ρ_e and wire cross-section A thus

$$Q = \rho_e A l \ . \tag{1}$$

There are two different forces that can act onto the moving electrons: the first one is due to the satellite moving in a magnetic field and called $\vec{F}_1$ (sometimes referred to as electromotive force), the second one is due to the movement of the electrons inside the wire and is called $\vec{F}_2$. We start by investigating $\vec{F}_2$, which can be expressed as

$$\vec{F}_2 = Q\vec{v}_e \times \vec{B} = -I\vec{l} \times \vec{B} \ , \tag{2}$$

where $\vec{v}_e$ is the velocity of the electrons in the wire. By a suitable orientation of the device—i.e. of the direction of the vector $\vec{l}$—the force $\vec{F}_2$ can be aligned tangential to the trajectory of the satellite and thus may change the semi-major axis of the orbit.

Though this explains the basic working principle of the device, the importance of the force $\vec{F}_1$ should be recognized as well. Of course, $\vec{F}_1$ vanishes as a force acting on the *whole* satellite, as the latter is neutral if charging effects are disregarded. However, locally the picture is quite different. Indeed the Lorentz force acting on the electrons in the wire due to the velocity of the satellite becomes

$$\vec{F}_1 = Q(\vec{v}_s - \vec{\omega}_e \times \vec{r}) \times \vec{B} = Q\vec{v}_{\mathit{eff}} \times \vec{B} \;, \tag{3}$$

with $\vec{v}_s$ being the velocity of the satellite, $\vec{\omega}_e$ the earth angular velocity and $\vec{B}$ the earth magnetic field. The first term in (3) is the well-known Lorentz force acting on a charge moving in the magnetic field, the second term the effect of the co-rotational electric field $\vec{E} = -(\vec{\omega}_e \times \vec{r}) \times \vec{B}$ which is due to the rotation of the core of the Earth (a conducting plasma) inside the magnetic field. The effect of $\vec{F}_1$ is to accelerate or decelerate the electrons thus creating the electromotive force (emf) also discussed by Cosmo and Lorenzini[1] for the electrodynamic tethers. In the first case it will be used as a source of energy, in the second case it must be counteracted by an electromagnetic potential. The fact that an opposite force acts onto the ions in the wire is not of importance any more, as they do not contribute to the flowing current.

The shielding of the magnetic field by a superconducting cylinder plays an important role in our concept and thus we should look at this effect a little bit more in detail. Certainly this is not a problem for a superconductor at rest. However, our device is supposed to move inside the magnetic field and as explained above it is the effect of this motion (viz. the Lorentz force) that we want to use. Let us simplify for a moment the situation and disregard the curvature of the motion of the satellite as well as the variations of the magnetic field. Then a homogeneous and static magnetic field is encountered, wherein the satellite moves uniformly in a direction perpendicular to the magnetic field (we assume the idealized situation of figure 1). Now a Lorentz transformation can be applied in such a way that the device is at rest in the new reference frame. Consider a situation where the device moves in the original frame in the x-direction at a constant speed v and where the magnetic field is simply $\vec{B} = (0, 0, B)$. The general Lorentz transformation of electric and magnetic fields read[21]

$$\vec{E}' = \gamma(\vec{E} + \vec{\beta} \times \vec{B}) - \frac{\gamma^2}{\gamma+1}\vec{\beta}(\vec{\beta} \cdot \vec{E}) \;, \qquad \vec{B}' = \gamma(\vec{B} - \vec{\beta} \times \vec{E}) - \frac{\gamma^2}{\gamma+1}\vec{\beta}(\vec{\beta} \cdot \vec{B}) \;, \tag{4}$$

with $\vec{\beta} = \vec{v}/c$ and $\gamma = (1-\beta^2)^{-1/2}$. Putting $\vec{\beta} = (0, 0, v/c)$ and all unprimed fields to zero except B_z it is seen that in the primed system the fields

$$\vec{E}' = (0, -\gamma\beta B, 0) \;, \qquad\qquad \vec{B}' = (0, 0, \gamma B) \tag{5}$$

are obtained, which means that an electric field parallel to the surface of the superconducting shield is encountered, which accounts for the Lorentz force in the coordinate system denoted by variables without primes. The effect of this electric field yields the force $\vec{F}_1$ and the current inside the superconductor must be shielded therefrom, whereas the picture for the emergence of $\vec{F}_2$ does not change. It is important to realize, that the superconductor shields the effect of this electric field onto the wire as well. Indeed, the electric field is parallel to the surface of the superconductor and therefore induces surface currents. As the superconductor has a finite length, this yields a non-trivial charge distribution at the surface of the superconductor that reaches a stable situation, when the electric field is canceled exactly inside the superconductor. In a more realistic situation, the electric field might not be exactly parallel to the surface of the superconductor. Nevertheless, only the compensation of the parallel component is important, while the perpendicular remains unimportant.

B. Propulsion

Let us have a closer look at the forces that can be used for propulsion. We split the force into radial and tangential part, where where $\hat{\vec{t}}$ is the direction perpendicular to $\vec{r}$ and $\vec{\omega}_e$. In our case the components of the force for $\vec{F}_2$ are

$$F_r = -I\hat{\vec{r}} \cdot (\vec{l} \times \vec{B}) \ , \tag{6}$$

$$F_t = -I\hat{\vec{t}} \cdot (\vec{l} \times \vec{B}) \ . \tag{7}$$

Which of the two components is relevant? As is obvious from Eq. (2) and Eq. (3) the device can work efficiently only if the magnetic field is almost perpendicular to the velocity and thus (for a small perturbation force) almost perpendicular to $\hat{\vec{t}}$. Thus we will consider, in this preliminary analysis, $F_t \gg F_r$ in contrast to a charged satellite (see Peck[22] for a description of Lorentz Augmented Orbit) where $F_t \ll F_r$.

For our explicit calculations we will make some assumptions about the exact orientation of the wire. It should be noticed that this is merely done to simplify the calculations and does affect the generality of the result obtained in this way. It is in fact one of the advantages of this device over electrodynamic tethers that its orientation in space can be controlled. If we aim at changing the semi-major axis of the spacecraft orbit (i.e. the orbit energy), the optimal geometry would be to have the magnetic field perpendicular to $\vec{v}_s$ and $\vec{v}_e$ and to orient $\vec{l}$ so that the Lorentz force is parallel to $\vec{v}_s$. Still this is not always possible (we cannot control the planet magnetic field direction) and the mission designers will have to use optimally the available thrusting direction to reach the mission goals, a very challenging optimal control problem in itself.

In the following we will assume that $\vec{v}_e$ is parallel to $\vec{v}_{\mathit{eff}} \times \vec{B}$, which can always be achieved by an appropriate rotation of the device. In this way the work performed by $\vec{F}_1$ on the current is maximized. Furthermore the current represents the flow of positive charges, $I = -\rho_e A v_e$, and we assign a certain resistance R to the wire.

To calculate the power we gain or need due to $\vec{F}_1$ we assume a constant (or at least slowly varying) value of the Lorentz force and in addition set the total length of the wire to $2l$. Then the power induced by $\vec{F}_1$ becomes

$$\begin{aligned} P_1 &= -I \int_{\text{wire}} \mathrm{d}\vec{l}\vec{v}_{\mathit{eff}} \times \vec{B} - 2RlI^2 \ , \\ &= -IBlv_{\mathit{eff}} \sin\alpha - 2RlI^2 \ , \end{aligned} \tag{8}$$

where α is the angle between $\vec{v}_{\mathit{eff}}$ and $\vec{B}$. The relation between the sign of P_1 and the direction of the force $\vec{F}_2$ is the same as in the case of a electrodynamic tether: below the geostationary (or more exactly magnetostationary) orbit, P_1 is negative if $\vec{F}_2$ acts as a propulsive force and vice versa. When crossing the geostationary orbit, the term $\vec{F}_1$ in Eq. (3) (and therefore also P_1) changes sign as v_{eff} becomes negative, while the term $\vec{F}_2$ in Eq. (2) does not. Therefore in this region the device acts as a propellantless and powerless propulsion system. Here we assumed a prograde orbit, in the case of a retrograde orbit the region of powerless propulsion does not exist.

Finally we can express the current I by means of (3) in terms of the power we need or gain:

$$\begin{aligned} I &= \frac{1}{4Rl}\left(Blv_{\mathit{eff}}\sin\alpha - \sqrt{(Blv_{\mathit{eff}}\sin\alpha)^2 + 8RlP_1}\right) \\ &= \frac{-P_1}{Blv_{\mathit{eff}}\sin\alpha} \qquad (R \to 0) \end{aligned} \tag{9}$$

In this way, a direct relation between the power P_1 in Eq. (8) and the force in Eq. $\vec{F}_2$ (2) can be made.

We want to go a little bit further and calculate the orbital change due to the applied force for a satellite in an equatorial and circular orbit. The total energy of such a system ($\mu = GM$ is the standard gravitational parameter)

$$E = \frac{1}{2}mv^2 - \mu\frac{m}{r} \ , \tag{10}$$

under the assumption of a small perturbing force, to leading order in the expansion $v = \sqrt{\mu/r} +$ corrections becomes

$$E = -\frac{m\mu}{2r} \tag{11}$$

and therefore

$$\frac{\mathrm{d}r}{\mathrm{d}t} = \frac{2r^2}{m\mu}\frac{\mathrm{d}E}{\mathrm{d}t} \ . \tag{12}$$

Here $\mathrm{d}E/\mathrm{d}t$ is the "propulsive power" and it is not necessarily related to Eq. (8). The propulsive power is an effect of the force (2), which tries to accelerate the spacecraft and thus

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \frac{\mathrm{d}E}{\mathrm{d}v}\frac{\mathrm{d}v}{\mathrm{d}t} = \pm\sqrt{\frac{\mu}{r}}F_2 \sin\alpha \ , \tag{13}$$

where a positive sign implies that the force propels while a minus sign indicates a breaking force. In this way we obtain the known formula for $\mathrm{d}r/\mathrm{d}t$, which for our special case reads

$$\frac{\mathrm{d}r}{\mathrm{d}t} = \pm\frac{2r^{3/2}}{m\sqrt{\mu}} IlB \sin\alpha \ . \tag{14}$$

III. Applications

A. Drag compensation

A possible application is drag compensation for satellites on a (not too) low orbit. The simplest model of a drag force is

$$F_{drag} = -\frac{1}{2}\rho_{atm} C_D A v_{atm}^2 \ , \tag{15}$$

where ρ_{atm} is the atmospheric density, A the area of the satellite v_{atm} the relative velocity of the satellite in the atmosphere and C_D a numerical coefficient. Assuming a circular orbit the force F_t becomes (notice that $\vec{l}$ is anti-parallel to $\vec{v}_e$ and thus anti-parallel to $\vec{t} \times \vec{B}$)

$$F_t = -IlBsin\alpha = \frac{P_1}{v_{eff}} \ . \tag{16}$$

The power needed to compensate the drag therefore can be written as

$$|P_1| = \frac{1}{2}\rho_{atm} C_D A v_{atm}^2 v_{eff} \ . \tag{17}$$

In order to give a rough estimate we assume in the following $v_{atm} = v_{eff}$ and $\sin\alpha = 1$. In addition we take the magnetic field as a dipole with strength

$$B(r) \approx \frac{8.04 \times 10^{15}}{r^3[m^3]} \text{Tesla.} \tag{18}$$

The results for a value of $C_D = 2.2$ are summarized in table 1. The needed power increases much faster than the necessary current, so the main restriction is expected therefrom. Still, it is remarkable that even at an altitude of 150km the necessary currents remain at a realistic order of magnitude, which should allow to compensate the drag of a spacecraft with a wire of about 1m length.

altitude [km]	ρ_{atm} [kg/m^3]	v_{eff} [m/s]	P_1/A [W/m^2]	Il [A m]
100	$4.79 \cdot 10^{-7}$	$7'434$	$211 \cdot 10^3$	$960 \cdot 10^3$
150	$1.65 \cdot 10^{-9}$	$7'369$	797	$3'742$
200	$2.53 \cdot 10^{-10}$	$7'306$	109	528
250	$6.24 \cdot 10^{-11}$	$7'272$	26.4	131

Table 1. Results for drag compensation.

B. Orbital transfers

In this section we will present some estimates on the use of our device as a propellantless propulsion system. We can distinguish three different cases:

Below geostationary orbit In this region propulsion does not come for free, but a certain amount of electrical power has to be provided to establish a propulsive current I. Therefore two different technological limitations can arise:

1. The propulsive force is proportional to the current, which is limited by the characters of the wire. Here we assume the wire to be superconducting as well and the limiting current is the critical current, above which the wire switches into the non-superconducting phase. Accordingly the resistance R in Eq. (8) will be set to zero.
2. Below geostationary orbit the maximal available power can be the important technological limit as well. This suggests to study situations where the available power is kept fixed.

Above geostationary orbit In Earth orbit the only reasonable technological limit is the critical current of the wire, which should be reachable by means of an adjustable resistance put into the closed wire. The necessity of high currents is illustrated by comparing the propulsive force (2) to the gravitational attraction. While the leading term of the latter falls off like $1/r^2$, the leading contribution from the former (the magnetic dipole) behaves like $1/r^3$. Therefore the propulsive force decreases by one power faster than the gravitational attraction, which must be compensated at large values of r by high currents and/or a long wire.

The picture may change in Jovian orbit. While most interesting applications are above the geostationary orbit, power nevertheless can turn out to be an issue. While propeling the spacecraft the device actually produces power, whose amount due to the strong magnetic field is much bigger than in Earth orbit. While parts of it may be used for power supply, a reasonable part is expected to be superfluous and must be gotten rid of. Limits thereon again can yield limits on the maximal acceptable power.

From this we conclude that the differential equation (14) should be solved for two different cases, either with the current kept fixed or with the available power kept fixed. In the first case the integration is straightforward and the result becomes

$$r(t) = \left(\frac{5B_0 r_B^3 Il \sin\alpha}{m\sqrt{\mu}} t + r_0^{5/2} \right)^{5/2} , \tag{19}$$

where $B_0 r_B^3 = 8.04 \times 10^{15} Tm^3$ for the earth magnetic field according to Eq. (18).

More complicated is the case where constant power is considered. The ensuing differential equation

$$r^{-3/2} \left(\sqrt{\frac{\mu}{r}} - \frac{2\pi r}{T} \right) \mathrm{d}r = \frac{2P}{m\sqrt{\mu}} \mathrm{d}t \tag{20}$$

has the solution

$$\left(\frac{4\pi\sqrt{r_0}}{T} + \frac{\sqrt{\mu}}{r_0} - \frac{2P}{m\sqrt{\mu}} t \right) r - -\sqrt{4\pi} T r^{3/2} - \sqrt{\mu} = 0 \ . \tag{21}$$

In these equation P is positive if power must be provided (below GEO) and negative if power is obtained (above GEO).

1. *Constant current $I = I_c$*

As is seen from Eq. (19) the transfer depends linearly on the the combination tIl/m, while the force scales linearly with Il. Given the fact that critical currents of the order of $10^5 - 10^6$A/cm^2 are realistic,[12–15] it is justified to assume a value of $Il/m \approx 10^3$A m/kg. This means in particular that the results in table 2 for a spacecraft of 1000kg assume a 1m long wire exposed to the magnetic field. are obtained, where we have set $\sin\alpha = 1$ for simplicity. As is seen the technological limit at low orbit most probably is the available power and not the critical current.

2. *Constant power*

This scenario makes sense below geostationary orbit, only. Starting at $r = 7000km$ with a power of 1W/kg the transfer times and maximal currents as displayed in table 3 are obtained (for completeness the minimal strength of the magnetic field is indicated as well). For a spacecraft of 1000kg and a wire of 1m the third column gives the necessary current in units of 10^3A. Of course, the current now diverges as we approach the geostationary

$r_{init.} \rightarrow r_{fin.}$ [10^6 m]	t [d]	F_{max}/m [mN/kg]	P_{max}/m [W/kg]
$10 \rightarrow 20$	8.46	8.0	44.9
$20 \rightarrow 30$	18.1	1.0	3.02
$30 \rightarrow 40$	29.8	0.3	0.436
$40 \rightarrow 50$	43.4	0.13	
$50 \rightarrow 60$	58.6	0.064	
$60 \rightarrow 70$	75.4	0.037	
$70 \rightarrow 80$	93.4	0.023	

Table 2. Results in Earth orbit with a constant current $Il/m = 10^3$Am/kg.

r_{final} [km]	t [days]	Il/m [Am/kg]	B_{min} [10^{-6} T]
10'000	90.2	22.3	8.03
15'000	155	103	2.4
20'000	184	331	1.05
25'000	198	894	0.515
30'000	205	2294	0.298
35'000	209	6429	0.188
40'000	210	32116	0.126

Table 3. Results in Earth orbit with a constant power of 1 W/kg.

orbit. The same is true for the propulsive force, though in a much weaker way; while I is proportional to $1/(Bv_{eff})$ the force just diverges as $1/v_{eff}$.

C. Going to Jupiter

As a further example we estimate roughly how this would look for a satellite in a prograde orbit of Jupiter. For the Jovian magnetic field we take

$$B(r) = \frac{1.25 \times 10^{21}}{r^3[km^3]} T, \tag{22}$$

all other assumptions are analogous to the ones of the previous sections, in particular again a 1m long device for a 1000kg spacecraft is taken as a guide. We intend to start with Io ($r = 422'000$km) and to visit Europa ($r = 670'900$km), Ganymede ($r = 1'070'000$km) and Callisto ($r = 1'883'000$km). The results indeed provide very interesting transfer times. Though all orbits of the Jovian moons are well above the geostationary orbit and therefore

	t [d]	$\frac{F_{max}}{m}$ [$\frac{\text{mN}}{\text{kg}}$]	$\frac{P_{max}}{Il}$ [$\frac{\text{mW}}{\text{Am}}$]	$\frac{P_{min}}{Il}$ [$\frac{\text{mW}}{\text{Am}}$]
Io → Europa	5.3	17	946	431
Europa → Ganymede	17	4.1	431	181
Ganymede → Callisto	77	1.0	181	60.1

Table 4. Results in Jovian orbit. A constant current $Il/m = 10^3$Am/kg is assumed.

propulsion is propelentless and powerless one might ask about the power needed to keep the workability of the device (mainly the cooling of the superconductors.) The last two columns illustrate that these doubts are unwarrented due to the generated power from the non-vanishing resistence in Eq. (8) that balances the critical current of the superconducting wire; as an example the power provided by a current of 10^3Am ranges between 60W at Callisto's orbit up to 1kW at Io's. It is self-evident to try to benefit from this energy, but as can be seen the superfluous power and the ensuing heat on board of the spacecraft will be an issue. Therefore an alternative scenario where the total power that can be handeled is restricted to 100W/kg is presented.

	t [d]	Il/m [Am/kg]	B_{min} [10^{-6} T]
Io → Europa	32.4	232	4.14
Europa → Ganymede	45.3	553	1.02
Ganymede → Callisto	74.4	1654	0.187

Table 5. Results in Jovian orbit, where the total power produced has been restricted to 100 W/kg.

Of course, these numbers cover the circular spiraling out, only. A more realistic scenario should investigate the feasibility of a complete maneuver including the capture in Jovian orbit. Already at this point we have good reasons to be optimistic. As our device does not depend on the plasma density its possibilities in Jovian orbit are quite interesting when compared to electrodynamic tethers.[2]

D. Conclusions

In this paper we have presented an original device for propellantless propulsion in an external magnetic field based on a closed wire that is partially shielded from the magnetic field by means of a superconductive cylinder. Besides the basic working principles we gave estimates on the efficiency of such a device in the orbits of the Earth and Jupiter. As for all propulsive devices that rely on an external magnetic field its workability depends a lot on the specific environment, i.e. the planet considered as well as the characteristics of the orbit. The working principles of our device are similar to the ones of electrodynamic tethers. There exists, however, an important difference: as we use a closed wire the current need not be closed via the plasma and therefore the workability depends on the magnetic field, but not on the plasmasphere of the planet. On the other hand, our device depends on advanced technological concepts, whose workability in space and whose implications on the system design (such as the cooling of the superconductors etc.) have not yet been studied in detail. However, from the promising results presented in this work we are optimistic that these issues won't change basic advantages of our concept.

One of the main distinction to be made is between orbits above and below the magnetostationary orbit, resp. Above the device is not just propellantless, but actually also powerless, as the actual velocity and the velocity relative to the magnetic field have different signs. The device then works in a passive mode and is able to convert energy from the planet rotation into propulsion via the magnetic field. Below geostationary orbit this is no longer the case, propellantless propulsion is still possible but a certain amount of electrical power must be provided by the satellite. Considering breaking the situation is reversed.

Applications above the magnetostationary orbit have been shown to be promising in Jovian orbit. Thanks to its strong magnetic field, relevant forces can be obtained in this way and it was shown that a journey visiting the different Jovian moons can be done within a reasonable time. In Earth orbit applications above the geostationary orbit suffer from the weakness of the magnetic field, but can still yield interesting numbers. In contrast to this, orbits below the magnetostationary orbit should be considered more in detail here, though the device cannot work in its most efficient way in this region. Estimations have been made for applications in drag compensation and in orbital transfers, for both cases promising numbers are obtained.

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